

Vector Meson Photoproduction with an Effective Lagrangian in the Quark Model II: ω Photoproduction

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Abstract

An investigation of $\gamma p \rightarrow \omega p$ is presented in a constituent quark model approach. The sparse data in the large t region where the resonances dominate is well described within the model, while the diffractive behavior in the small t region requires an additional t-channel exchange. Taking into account the t-channel π^0 exchange, we find a good overall agreement with the available data with only 3 free parameters. Our study shows that the differential cross section is not sensitive to s-channel resonances, however, the polarization observables are demonstrated to be very sensitive. Thus, measuring polarization observables is the crucial part of the vector meson photoproduction program in the search for “missing” resonances.

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1. INTRODUCTION

The newly established electron and photon facilities have made it possible to investigate the mechanism of vector meson photoproduction on nucleons with much improved experimental accuracy. This has been motivated in part by the puzzle that the NRQM [1,2] predicts a much richer resonance spectrum than has been observed in $\pi N \rightarrow \pi N$ scattering experiments. Quark model studies have suggested that those resonances missing in the πN channel may couple strongly to, i.e., the ωN and ρN channels. Experiments have been performed at ELSA [3] and will be done at TJNAF in the near future [4]. Therefore, a theory on the reaction mechanism that highlights the dynamical role of s-channel resonances is crucial in order to interpret new experimental data.

Building on recent successes of the quark model approach to pseudoscalar meson photoproduction we have proposed [5] extending this approach to vector meson photoproduction. The focus of this paper is to present the numerical implementation of the reaction $\gamma p \rightarrow \omega p$ in the quark model framework. The reaction $\gamma p \rightarrow \omega p$ shares similar features with the reaction $\gamma p \rightarrow \eta p$ in the pseudoscalar sector, since both are isospin zero states. This eliminates contributions from all isospin 3/2 intermediate resonances, thus the signals from isospin 1/2 states, in particular those resonances “missing” in the πN channels, can be isolated. Thus, investigating the dynamical role of the s-channel resonances and examining which experimental observables are best suited to demonstrate the existence of these resonances is the primary goal of our study. However, an important question related to this discussion is whether additional t-channel exchanges responsible for the diffractive behavior in the small t region are needed. It has been proposed in the pseudoscalar sector that the extra t-channel exchanges could be excluded with the duality hypothesis [6]. In a study of kaon photoproduction by J.C. David *et al* [7], the inclusion of the additional s-, u-

channel resonances, particularly the higher partial wave resonances leads to smaller coupling constants for the t-channel K^* exchanges, indicating some phenomenological support for the duality argument. Similarly, one could also investigate the role of the t-channel exchanges in ω photoproduction by including the t-channel exchanges and treating the coupling constants as parameters. If the diffractive behavior could be described by contributions from a complete set of s- and u-channel resonances, the coupling constants for the t-channel exchanges should be very small. Thus, we include in our calculations the π^0 exchange suggested by Friman and Soyeur [8], who showed that the diffractive behavior in the low energy region can be well described through π^0 exchange.

In section 2, we give a brief description of our model, of which a complete framework has been given in Ref. [5]. The π^0 exchange model by Friman and Soyeur will be introduced in the standard helicity representation. The results of our calculations for the s- and u-channel transition amplitudes are given in section 3, and the conclusion are given in Section 4.

2. THE MODEL

The starting point of our quark model approach to vector meson photoproduction is the effective Lagrangian [5],

$$L_{eff} = -\bar{\psi}\gamma_\mu p^\mu\psi + \bar{\psi}\gamma_\mu e_q A^\mu\psi + \bar{\psi}(a\gamma_\mu + \frac{ib\sigma_{\mu\nu}q^\nu}{2m_q})\phi_m^\mu\psi, \quad (1)$$

where ψ and ϕ_m^μ are the quark and the vector meson fields, and a and b are coupling constants which will be determined by experimental data. At the tree level, the transition matrix element based on this Lagrangian in Eq.(1) can be written as the sum of contributions from s-, u- and t- channels,

$$M_{fi} = M_{fi}^s + M_{fi}^u + M_{fi}^t. \quad (2)$$

The first and second terms in Eq.(2) represent the s- and u-channel contributions, and a complete set of helicity amplitudes for each of the s-channel resonance below 2 GeV have been evaluated in the $SU(6) \otimes O(3)$ symmetry limit [5]. Resonances above 2 GeV are treated as degenerate in order to express contributions from resonances with a certain quantum number n in a compact form. The contributions from the u-channel resonances are divided into two parts as well. The first part contains the contributions from the resonances with the quantum number $n = 0$, which includes the spin 1/2 baryons, such as the Λ , Σ and the nucleons, and the spin 3/2 resonances, such as the Σ^* in K^* photoproduction and the $\Delta(1232)$ resonance in ρ photoproduction. Because the mass splitting between the spin 1/2 and spin 3/2 resonances with $n = 0$ is significant, they have to be treated separately. Since in ω photoproduction isospin 3/2 resonance cannot contribute due to isospin conservation, construction of the resonance contribution is simpler than in the case of ρ meson photoproduction. The second part comes from the excited resonances with quantum number $n \geq 1$. Since the contributions from the u-channel resonances are not sensitive to the precise mass positions, they are treated as degenerate as well. The transition matrix elements are written in the form of helicity amplitudes, which are 12 independent amplitudes and defined as in ref. [5,9],

$$\begin{aligned}
H_{1\lambda_V} &= \langle \lambda_V, \lambda_2 = +1/2 | T | \lambda = 1, \lambda_1 = -1/2 \rangle \\
H_{2\lambda_V} &= \langle \lambda_V, \lambda_2 = +1/2 | T | \lambda = 1, \lambda_1 = +1/2 \rangle \\
H_{3\lambda_V} &= \langle \lambda_V, \lambda_2 = -1/2 | T | \lambda = 1, \lambda_1 = -1/2 \rangle \\
H_{4\lambda_V} &= \langle \lambda_V, \lambda_2 = -1/2 | T | \lambda = 1, \lambda_1 = +1/2 \rangle,
\end{aligned} \tag{3}$$

where the helicity states are denoted by $\lambda = \pm 1$ for the incident photon, $\lambda_V = 0, \pm 1$ for the outgoing vector meson, and $\lambda_1 = \pm 1/2$, $\lambda_2 = \pm 1/2$ for the initial and final state nucleons, respectively. The various experimental observables, such as the cross

section and polarization observables, have been discussed in Ref. [9] in terms of these amplitudes. In particular, the differential cross section can be written as

$$\frac{d\sigma}{d\Omega_{c.m.}} = \frac{\alpha_e \omega_m (E_f + M_N)(E_i + M_N)}{8\pi s} |\mathbf{q}| \frac{1}{2} \sum_{a=1}^4 \sum_{\lambda_V=0,\pm 1} |H_{a\lambda_V}|^2 \quad (4)$$

in the center of mass frame, where \sqrt{s} is the total energy of the system, M_N represents the mass of the nucleon, ω_m denotes the energy of the meson with momentum \mathbf{q} , and E_i , E_f denote the energies of the initial and final nucleon states. As defined in Ref. [9], the four single-spin observables in *bilinear helicity product* (BHP) form have the following expressions:

$$\check{T} = -\frac{1}{2} \langle H | \boxed{\Gamma^{10}} \boxed{\omega^1} | H \rangle, \quad (5)$$

for the target polarization,

$$\check{P}_{N'} = \frac{1}{2} \langle H | \boxed{\Gamma^{12}} \boxed{\omega^1} | H \rangle, \quad (6)$$

for the polarization of the final nucleon,

$$\check{\Sigma} = \frac{1}{2} \langle H | \Gamma^4 \omega^A | H \rangle, \quad (7)$$

for the polarized photon asymmetry, and

$$\check{P}_V = \frac{1}{2} \langle H | \boxed{\Gamma^1} \boxed{\omega^3} | H \rangle, \quad (8)$$

for the polarization of the final vector meson, where the explicit expressions and conventions for the Γ and ω matrices have been given in Ref. [9]. The phase space factor for these four observables are the same as in the differential cross section, therefore, they are normalized by being divided by the differential cross section.

The t-channel exchange of M_{fi}^t in Eq.(2) would correspond to ω exchange which is absent since the photon cannot couple to the ω . However, an additional t-channel exchange is commonly included even though it is not a part of the Lagrangian in

Eq.(1). This is the π^0 exchange which is known to be needed in order to describe the diffractive behavior in the small t region. The Lagrangian for the π^0 exchange model has the following form [8],

$$L_{\pi NN} = -ig_{\pi NN}\bar{\psi}\gamma_5(\boldsymbol{\tau} \cdot \boldsymbol{\pi})\psi \quad (9)$$

for the πNN coupling vertex, and

$$L_{\omega\pi^0\gamma} = e_N \frac{g_{\omega\pi\gamma}}{M_\omega} \epsilon_{\alpha\beta\gamma\delta} \partial^\alpha A^\beta \partial^\gamma \omega^\delta \pi^0 \quad (10)$$

for the $\omega\pi\gamma$ coupling vertex, where the ω^δ and π^0 represent the ω and π^0 fields, the A^β denotes the electromagnetic field, and $\epsilon_{\alpha\beta\gamma\delta}$ is the Levi-Civita tensor, and M_ω is the mass of ω meson. The $g_{\pi NN}$ and $g_{\omega\pi\gamma}$ in Eqs. (9) and (10) denote the coupling constants at the two vertices, respectively. Therefore, the transition amplitudes of t-channel π^0 exchange have the following expression,

$$M_T^t = \frac{e_N g_{\pi NN} g_{\omega\pi\gamma}}{2M_\omega(t - m_\pi^2)} \{ \omega \boldsymbol{\epsilon} \cdot (\mathbf{q} \times \boldsymbol{\epsilon}_v) + \omega_m \mathbf{k} \cdot (\boldsymbol{\epsilon} \times \boldsymbol{\epsilon}_m) \} \boldsymbol{\sigma} \cdot \mathbf{A} e^{-\frac{(\mathbf{q}-\mathbf{k})^2}{6\alpha_\pi^2}} \quad (11)$$

for the transverse transition, and

$$M_L^t = -\frac{e_N g_{\pi NN} g_{\omega\pi\gamma}}{2M_\omega(t - m_\pi^2)} \frac{M_\omega}{|\mathbf{q}|} (\boldsymbol{\epsilon} \times \mathbf{k}) \cdot \mathbf{q} \boldsymbol{\sigma} \cdot \mathbf{A} e^{-\frac{(\mathbf{q}-\mathbf{k})^2}{6\alpha_\pi^2}} \quad (12)$$

for the longitudinal transition, where ω in the transition amplitudes denotes the energy of the photon with momentum \mathbf{k} , and $\mathbf{A} = -\frac{\mathbf{q}}{E_f + M_N} + \frac{\mathbf{k}}{E_i + M_N}$, and $t = (q - k)^2 = M_\omega^2 - 2k \cdot q$. The factor $e^{-\frac{(\mathbf{q}-\mathbf{k})^2}{6\alpha_\pi^2}}$ in Eqs. (11) and (12) is the form factor for both πNN and $\omega\gamma\pi$ vertices, if we assume that the wavefunctions for nucleon, ω and π have a Gaussian form. The constant α_π^2 in this form factor is treated as a parameter. Following the same procedure as in Ref. [5], the explicit expressions for the operators in terms of the helicity amplitudes can be obtained. They are listed in Tables 1 and 2 for the transverse and longitudinal amplitudes respectively.

3. RESULTS AND DISCUSSION

Before discussing the details of our numerical results, we point out that the nonrelativistic wavefunction in the quark model become more inadequate as the energy of the system increases. A procedure to partly remedy this problem is to introduce the Lorentz boost factor in the spatial integrals that involve the spatial wavefunctions of nucleons and baryon resonances,

$$R(q, k) \rightarrow \gamma_q \gamma_k R(q \gamma_q, k \gamma_k), \quad (13)$$

where $\gamma_q = \frac{M_f}{E_f}$ and $\gamma_k = \frac{M_i}{E_i}$. A similar procedure had been used in the numerical evaluation of pseudoscalar meson photoproduction [10].

There are four free parameters in the quark model approach to the s- and u-channel resonance contributions: the quark mass m_q , the harmonic oscillator strength α , and the coupling constants a and $b' = b - a$ from Eq. (1). Because the quark mass m_q and the parameter α are commonly used in the quark model, they are fixed at

$$\begin{aligned} m_q &= 330 \text{ MeV} \\ \alpha &= 410 \text{ MeV}. \end{aligned} \quad (14)$$

In addition to the free parameters in the s- and u- channels, there are also parameters in the t-channel π^0 exchange: the coupling constants for the πNN and $\omega\pi\gamma$ vertices, $g_{\pi NN}$ and $g_{\omega\pi\gamma}$, and the parameter α_π in Eqs. (11) and (12). We find that the s- and u-channel resonance contributions alone are unable to describe the diffractive behavior in the small t region. We therefore include the π^0 exchange using for the coupling constants $g_{\pi NN}$ and $g_{\omega\pi\gamma}$ [8]:

$$\begin{aligned} \frac{g_{\pi NN}^2}{4\pi} &= 14, \\ g_{\omega\pi\gamma}^2 &= 3.315, \end{aligned} \quad (15)$$

and find a good description of the diffractive behavior. Note that the values of $g_{\pi NN}$ and $g_{\omega\pi\gamma}$ were fixed by separate experiments and, therefore, are not free parameters in Ref. [8]. This suggest that the duality hypothesis may not work in vector meson photoproduction. The parameter α_π will be determined from ω photoproduction data along with the coupling constants a and b' . Qualitatively, we would expect that α_π be smaller than the parameter $\alpha = 410$ MeV, since it represents the combined form factors for both πNN and $\omega\pi\gamma$ vertices while the parameter α only corresponds to the form factor for the πNN or ωNN vertex alone.

In Table 3, we list the s-channel resonances that contribute to the ω photoproduction in $SU(6) \otimes O(3)$ symmetry limit. The masses and widths of these resonances come from the recent Particle Data Group [11]. It should be noted that the Moorhouse selection [12] rule have eliminated the states belonging to $[70, 1^-]_1$ and $[70, 2^+]_2$ representation with symmetric spin structure from contributing to the ω photoproduction with the proton target so that the s-channel states $S_{11}(1650)$, $D_{13}(1700)$, $D_{15}(1650)$ are not present in our numerical evaluations. Of course, configuration mixing will lead to additional contributions from these resonances which, however, cannot be determined at present due to the poor quality of data.

In Table 3 we also list the partial widths of the resonances decaying into the ωN channel and their photon decay helicity amplitudes. In terms of the helicity amplitudes, the partial width Γ_ω of a resonance with spin J decaying into an ω meson and a nucleon is

$$\Gamma_\omega = \frac{|\mathbf{q}|\omega_m M_N}{4\pi M_R} \frac{8}{2J+1} \{ |A_{\frac{1}{2}}|^2 + |A_{\frac{3}{2}}|^2 + \frac{M_\omega^2}{|\mathbf{q}|^2} |S_{\frac{1}{2}}|^2 \}, \quad (16)$$

where $A_{\frac{1}{2}}$, $A_{\frac{3}{2}}$ and $S_{\frac{1}{2}}$ represent the vector meson helicity amplitudes and M_R denotes the mass of the intermediate resonance. The partial width Γ_γ of the resonances decaying into γN , and contributing to ω photoproduction, is

$$\Gamma_\gamma = \frac{\mathbf{k}^2}{\pi} \frac{2M_N}{(2J+1)M_R} \{|A_{\frac{1}{2}}^\gamma|^2 + |A_{\frac{3}{2}}^\gamma|^2\}, \quad (17)$$

where $A_{\frac{1}{2}}^\gamma$ and $A_{\frac{3}{2}}^\gamma$ denote the photon helicity amplitudes.

Only the resonances $P_{13}(1900)$ and $F_{15}(2000)$, at present classified as 2-star resonances in the 1996 PDG listings, have masses above the ω decay threshold, and therefore have branching ratio into the ωN channel. We find that the $F_{15}(2000)$ has a larger decay width than the $P_{13}(1900)$. This finding differs from Ref. [2], where the $P_{13}(1900)$ was calculated to have the larger width into the ωN channel. The photon decay helicity amplitudes in Table 3 are consistent with previous theoretical results of the NRQM approach in Ref. [1]. Qualitatively, the resonance $F_{15}(2000)$ plays a very important role in ω photoproduction. Of course, since our investigation here is exploratory it can only provide an approximate description of the resonance contributions; a more accurate approach to the intermediate resonance decay should be adopted in a systematic analysis [5].

We have not performed a rigorous numerical fit to the available data because of the poor quality of the data. Our study suggests that the parameters a , b' and α_π with the values

$$\begin{aligned} a &= -2.2, \\ b' &= 3.0, \\ \alpha_\pi &= 300 \text{ MeV} \end{aligned} \quad (18)$$

gives a good description of the differential cross section data [3] in the resonance region. Clearly, these parameters have considerable uncertainties.

Fig. 1 shows our calculations for the differential cross section at the average photon energies of $E_\gamma = 1.225, 1.45, 1.675$ and 1.915 GeV, in comparison with the data [3]. The results for the t-channel π^0 exchange and contributions from only the s- and u-channel processes are also shown separately. Our results with the π^0 exchange

are consistent with the findings of Ref. [8] although the form factor in our calculation is different. Fig. 1 clearly demonstrates that the t-channel π^0 exchange is dominant in the small angle region, while the s- and u-channel resonance contributions become more important as the scattering angle θ increases. To test the sensitivity of s-channel resonances to the differential cross section, the angular distribution at 1.675 GeV is presented with and without the contribution from the resonance $F_{15}(2000)$; its threshold energy is around 1.675 GeV in the lab. frame. The results indicate that the differential cross section data alone are not sufficient to determine the presence of this resonance considering the theoretical and experimental uncertainties. Since the resonance couplings of the $F_{15}(2000)$ are larger than those of other resonances in this mass region, the sensitivity of the differential cross section to other resonances around 2 GeV is even smaller.

In contrast to the differential cross section, the polarization observables show a much more dramatic dependence on the presence of the s-channel resonances. We present results of four single polarizations at 1.675 GeV in Fig. 2. The absence of the resonance $F_{15}(2000)$ leads to a sign change in the target polarization, and the variations in the recoil as well as the meson polarization observable are very significant as well. The absence of the resonance $P_{13}(1900)$, also shown in Fig. 2, leads to very significant changes in the recoil polarization. Although we do not expect our numerical results to give a quantitative prediction of polarization observables at the present stage, since the calculations are limited to the $SU(6) \otimes O(3)$ symmetry limit that should be broken in more realistic quark model wavefunction, our results clearly suggest that the polarization observables may be the best place to determine s-channel resonance properties.

Our results for the total cross section are shown in Fig. 3, in which the contributions from the s- and u-channel resonances alone are compared to the full calculation.

Our results indicate an increasing discrepancy between theory and the data [3,19,20] with increasing energy E_γ . This discrepancy comes mainly from the small angle region where the π^0 exchange alone is not sufficient to describe the diffractive behavior at higher energies. One might expect that Pomeron exchange [14,17] plays a more important role in the higher energy region. However, Fig. 1 shows that our results for the differential cross section at the large angle region are in good agreement with the data, and it suggests that contributions from the s- and u- channel resonances which are the main focus of our study, give an appropriate description of the reaction mechanism.

It is interesting to note that the small bump around 1.7 GeV in the total cross section comes from the contributions of the resonance $F_{15}(2000)$. As discussed above, our calculations find that the resonance $F_{15}(2000)$ has a strong coupling to the ω N channel. Thus, this resonance is perhaps the best candidate whose existence as a “missing” resonance can be established through ω photoproduction.

5. CONCLUSION

In conclusion, we have presented a study for ω photoproduction on the nucleon at low and intermediate energies. Our results indicate that s- and u-channel resonances alone are insufficient at small t and that additional t-channel contributions are necessary to describe the large diffractive behavior. We find that the s- and u-channel resonance contributions are important in the large scattering angle region. The differential cross section alone is insufficient to determine s-channel resonance properties in ω photoproduction, however, polarization observables are demonstrated to be very sensitive to the presence of individual s-channel resonances. It is therefore imperative to perform polarization measurements in future programs on vector meson photoproduction. Our numerical results suggest that properties of the resonance

$F_{15}(2000)$ could be well determined with precise ω photoproduction data. Given the few free parameters in this approach, the agreement with the data, especially in the large scattering angle region, is satisfactory. Clearly, an improved determination of s-channel resonance properties requires a systematic analysis of all photoproduction data. Due to the small number of free parameters the quark model approach is an appropriate tool for this important task.

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TABLES

TABLE I. The operators appearing in the longitudinal π^0 exchange expressed in terms of helicity amplitudes. $\hat{\mathbf{k}}$ and $\hat{\mathbf{q}}$ are the unit vectors of \mathbf{k} and \mathbf{q} , respectively. The d functions depend on the rotation angle θ between \mathbf{k} and \mathbf{q} . All other components of $H_{a\lambda_V}$ are zero. $\lambda_f = \pm\frac{1}{2}$ denotes the helicity of the final state nucleon..

Operators	$H_{10}(\lambda_f = \frac{1}{2})$	$H_{20}(\lambda_f = \frac{1}{2})$
	$H_{30}(\lambda_f = -\frac{1}{2})$	$H_{40}(\lambda_f = -\frac{1}{2})$
$(\boldsymbol{\epsilon} \times \hat{\mathbf{k}}) \cdot \hat{\mathbf{q}} \boldsymbol{\sigma} \cdot \hat{\mathbf{q}}$	$i\sqrt{2}d_{10}^1 d_{10}^1 d_{\frac{1}{2}\lambda_f}^{\frac{1}{2}}$ $-id_{10}^1 d_{00}^1 d_{-\frac{1}{2}\lambda_f}^{\frac{1}{2}}$	$i\sqrt{2}d_{10}^1 d_{-10}^1 d_{-\frac{1}{2}\lambda_f}^{\frac{1}{2}}$ $+id_{10}^1 d_{00}^1 d_{\frac{1}{2}\lambda_f}^{\frac{1}{2}}$
$(\boldsymbol{\epsilon} \times \hat{\mathbf{k}}) \cdot \hat{\mathbf{q}} \boldsymbol{\sigma} \cdot \hat{\mathbf{k}}$	$-id_{10}^1 d_{-\frac{1}{2}\lambda_f}^{\frac{1}{2}}$	$id_{10}^1 d_{\frac{1}{2}\lambda_f}^{\frac{1}{2}}$

TABLE II. The operators appearing in the transverse π^0 exchange expressed in terms of helicity amplitudes. $\hat{\mathbf{k}}$ and $\hat{\mathbf{q}}$ are the unit vectors of \mathbf{k} and \mathbf{q} , respectively. The d functions depend on the rotation angle θ between \mathbf{k} and \mathbf{q} . $\lambda_V = \pm 1$ denotes the helicity of ω meson, and $\lambda_f = \pm \frac{1}{2}$ denotes the helicity of the final nucleon.

Operators	$H_{1\lambda_V}(\lambda_f = \frac{1}{2})$	$H_{2\lambda_V}(\lambda_f = \frac{1}{2})$
	$H_{3\lambda_V}(\lambda_f = -\frac{1}{2})$	$H_{4\lambda_V}(\lambda_f = -\frac{1}{2})$
$(\boldsymbol{\epsilon} \times \boldsymbol{\epsilon}_v) \cdot \hat{\mathbf{q}} \boldsymbol{\sigma} \cdot \hat{\mathbf{q}}$	$i\sqrt{2}\lambda_V d_{1\lambda_V}^1 d_{10}^1 d_{\frac{1}{2}\lambda_f}^{\frac{1}{2}}$ $-i\lambda_V d_{1\lambda_V}^1 d_{00}^1 d_{-\frac{1}{2}\lambda_f}^{\frac{1}{2}}$	$i\sqrt{2}\lambda_V d_{1\lambda_V}^1 d_{-10}^1 d_{-\frac{1}{2}\lambda_f}^{\frac{1}{2}}$ $+i\lambda_V d_{1\lambda_V}^1 d_{00}^1 d_{\frac{1}{2}\lambda_f}^{\frac{1}{2}}$
$(\boldsymbol{\epsilon} \times \boldsymbol{\epsilon}_v) \cdot \hat{\mathbf{q}} \boldsymbol{\sigma} \cdot \hat{\mathbf{k}}$	$-i\lambda_V d_{1\lambda_V}^1 d_{-\frac{1}{2}\lambda_f}^{\frac{1}{2}}$	$i\lambda_V d_{1\lambda_V}^1 d_{\frac{1}{2}\lambda_f}^{\frac{1}{2}}$
$(\boldsymbol{\epsilon} \times \boldsymbol{\epsilon}_v) \cdot \hat{\mathbf{k}} \boldsymbol{\sigma} \cdot \hat{\mathbf{q}}$	$i\sqrt{2}d_{1\lambda_V}^1 d_{10}^1 d_{\frac{1}{2}\lambda_f}^{\frac{1}{2}}$ $-id_{1\lambda_V}^1 d_{00}^1 d_{-\frac{1}{2}\lambda_f}^{\frac{1}{2}}$	$i\sqrt{2}d_{1\lambda_V}^1 d_{-10}^1 d_{-\frac{1}{2}\lambda_f}^{\frac{1}{2}}$ $+id_{1\lambda_V}^1 d_{00}^1 d_{\frac{1}{2}\lambda_f}^{\frac{1}{2}}$
$(\boldsymbol{\epsilon} \times \boldsymbol{\epsilon}_v) \cdot \hat{\mathbf{k}} \boldsymbol{\sigma} \cdot \hat{\mathbf{k}}$	$-id_{1\lambda_V}^1 d_{-\frac{1}{2}\lambda_f}^{\frac{1}{2}}$	$id_{1\lambda_V}^1 d_{\frac{1}{2}\lambda_f}^{\frac{1}{2}}$

TABLE III. The resonance states contributing in $\gamma p \rightarrow \omega p$. The star “*” denotes the current determination status of the resonances as defined in PDG(1996). The partial width of resonances decaying into ωN and the photon decay helicity amplitudes $A_{\frac{1}{2}}^\gamma$ and $A_{\frac{3}{2}}^\gamma$ are given by our model. “-” denotes that those states are below the threshold of ω production or the amplitudes decouple for the states.

Resonance	$SU(6)$ State	Width (MeV)	$\sqrt{\Gamma_\omega}$ ($\text{MeV}^{-\frac{1}{2}}$)	$\sqrt{\Gamma_\gamma}$ ($\text{MeV}^{-\frac{1}{2}}$)	$A_{\frac{1}{2}}^\gamma$	$A_{\frac{3}{2}}^\gamma$
$S_{11}(1535)^{****}$	$N(^2P_M)_{\frac{1}{2}-}$	150	-	2.67	+172.4	-
$D_{13}(1520)^{****}$	$N(^2P_M)_{\frac{3}{2}-}$	120	-	0.31	-51.8	+122.5
$P_{13}(1720)^{****}$	$N(^2D_S)_{\frac{3}{2}+}$	150	-	0.61	-113.6	+38.0
$F_{15}(1680)^{****}$	$N(^2D_S)_{\frac{5}{2}+}$	130	-	0.10	0	+78.5
$P_{11}(1440)^{****}$	$N(^2S'_S)_{\frac{1}{2}+}$	350	-	0.03	-37.4	-
$P_{11}(1710)^{***}$	$N(^2S_M)_{\frac{1}{2}+}$	100	-	0.12	-37.7	-
$P_{13}(1900)^{**}$	$N(^2D_M)_{\frac{3}{2}+}$	400	1.40	0.48	+90.4	-25.8
$F_{15}(2000)^{**}$	$N(^2D_M)_{\frac{5}{2}+}$	200	5.12	0.09	+28.6	-49.9

FIGURE CAPTIONS:

1. The differential cross sections (solid curves) for $\gamma p \rightarrow \omega p$ at $E_\gamma = 1.225, 1.45, 1.675$ and 1.915 GeV. The data come from Ref. [3]. The π^0 exchanges are shown by the dashed curves and the contributions from s- and u-channel exclusively are shown by the dotted curves. In (c), the dot-dashed curve represents the differential cross section without contributions from the resonance $F_{15}(2000)$.
2. The four single-spin polarization observables in $\gamma p \rightarrow \omega p$ are given by the solid curves at $E_\gamma = 1.675$ GeV. The dotted curves correspond to the asymmetries without the resonance $F_{15}(2000)$, while the dashed curves to those without the resonance $P_{13}(1900)$.
3. The total cross section of $\gamma p \rightarrow \omega p$ are fitted by the solid curve with π^0 exchange taken into account. The dotted curve describes the pure contributions from s- and u-channel. The data are from [3](triangle), [19] and other experiments(square).





